Journal of Tropical Crop Science Vol. 13 No. 1, February 2026
www.j-tropical-crops.com

Received 10/05/2025; Revised 06/10/2025; Accepted 17/10/2025
https://doi.org/10.29244/jtcs.13.01.134-147

REVIEW PAPER

The Potential of *Metarhizium anisopliae* (Metsch.) Sorokīn as the Biocontrol Agent Against Cacao Pod Borer (*Conopomorpha cramerella* Snellen)

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Abstract

Metarhizium anisopliae (Metsch.) Sorokīn is an entomopathogenic fungus with broad bio-insecticidal potential, widely recognized for its role in sustainable pest management. This review examines the taxonomy, pathogenesis, infection symptoms, environmental requirements, host specificity, and dual role as both a biocontrol agent and an endophyte. Special emphasis is placed on its efficacy against the cacao pod borer (*Conopomorpha cramerella* Snellen), a significant pest in Southeast Asia that causes yield losses exceeding 50% in cacao plantations. Laboratory and semi-field studies report larval mortality rates of up to 80%–90% under controlled conditions. However, field-level efficacy varies due to environmental factors such as temperature, relative humidity, UV exposure, and soil characteristics. The review also discusses formulation strategies, including conidial suspensions and granular formulations, that improve fungal persistence and infection success. Despite promising outcomes, the effectiveness of *M. anisopliae* is influenced by strain variability, local adaptation, and integration with cultural practices. Understanding these dynamics is crucial for optimizing the application of this approach in integrated pest management (IPM) systems and advancing sustainable cacao production.

Keywords: colonization, entomopathogenicity, formulation, mycoinsecticide, symbiosis

Introduction

Cacao (*Theobroma cacao* L.) is a globally significant crop that underpins the livelihoods of over five million smallholder farmers in tropical regions and serves as the foundation of the multibillion-dollar chocolate industry (Adeniyi & Asogwa, 2023). In Southeast Asia, particularly in the Philippines, Indonesia, and Malaysia, cacao has been identified as a strategic commodity for rural development and poverty alleviation due to its export potential and contribution to growers' income (Patalinghug, 2022; Rizal et al., 2024). However, cacao production faces persistent challenges from insect pests and diseases, among which the cacao pod borer (*Conopomorpha cramerella* Snellen, CPB) is considered the most destructive pest (Amalin et al., 2023; Magfirah et al., 2025).

The cacao pod borer causes direct economic losses through extensive pod damage and deterioration of bean quality, resulting in yield reductions exceeding 50% (Adeniyi & Asogwa, 2023). Larvae penetrate the cacao pod and feed on the mucilage and developing beans, leading to shriveled, discolored seeds and poor fermentation quality (Meilin et al., 2023; Prasad,

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2022). External symptoms include brownish lesions, premature ripening, and frass and silk webbing (Cocuzza et al., 2021). These damages not only reduce marketable yield but also increase postharvest losses, forcing farmers to rely heavily on chemical insecticides and labor-intensive practices such as pod sleeving (Meilin et al., 2023; Rizal et al., 2024). However, continuous chemical use poses health and ecological risks and can lead to pest resistance and disruption of beneficial insect populations (Pathak et al., 2022).

To address these challenges, biological control using entomopathogenic fungi has emerged as a sustainable alternative within integrated pest management (IPM) systems (Rajput et al., 2024; Zhou et al., 2024). Among these fungi, *Metarhizium anisopliae* (Metsch.) Sorokin is one of the most studied species due to its broad host range and high virulence against over 200 insect pests, including Lepidoptera, Coleoptera, and Diptera (Sharma & Sharma, 2021; Yapa et al., 2025). *Metarhizium anisopliae* is a naturally occurring soil-borne fungus that infects insects through conidial adhesion, enzymatic cuticle degradation, and internal colonization, leading to host mortality (Karthi et al., 2024; Ma et al., 2024). The infection results in the characteristic green muscadine disease, marking the completion of its pathogenic cycle (Nwaokolo et al., 2023).

In cacao ecosystems, *M. anisopliae* has demonstrated promising biocontrol potential against CPB, achieving larval mortality rates of 80%–90% under both laboratory and semi-field conditions (Aryal et al., 2025; Ernawati, 2013; Montecalvo & Navasero, 2021). Field trials, however, reveal variable efficacy influenced by environmental factors such as temperature, humidity, UV exposure, and fungal strain adaptation (Quesada-Moraga et al., 2024; Sani et al., 2023). Despite these limitations, *M. anisopliae* remains a viable component of eco-friendly pest management due to its safety, compatibility with cultural control methods, and potential endophytic relationship with cacao plants (Aravinthraju et al., 2024; Behie et al., 2015).

From an economic standpoint, adopting *M. anisopliae* can reduce reliance on costly chemical inputs, lower production costs over time, and promote environmental sustainability (de Sousa et al., 2025). For smallholder cacao growers, integrating *M. anisopliae* into pest management could improve yield stability, enhance bean quality, and support access to sustainable and fair-trade markets that prioritize environmentally responsible practices.

Therefore, this review aims to synthesize the current literature on *M. anisopliae* as a biological control agent against the cacao pod borer, with an emphasis on its taxonomy, infection mechanism, host specificity, endophytic potential, and environmental requirements. The paper further evaluates its economic implications, identifies research gaps, and discusses the importance of strain selection and integrated management approaches for sustainable cacao production.

Literature Review Methods

This review was conducted through a systematic literature search to identify relevant studies on *Metarhizium anisopliae* (Metsch.) Sorokin as a biocontrol agent for cacao pod borer (*Conopomorpha cramerella* Snellen, CPB). Literature was retrieved from online databases including Scopus, Web of Science, and Google Scholar. Search terms used included *Metarhizium anisopliae*, cacao pod borer, CPB, biological control, and entomopathogenic fungi.

Inclusion criteria were: (1) peer-reviewed articles, (2) studies focusing on *M. anisopliae* or related entomopathogenic fungi applied to CPB management, (3) publications between 2007 and 2025, and (4) studies reporting laboratory, greenhouse, or field trial results. Exclusion criteria included non-English publications, review articles not focused on CPB, and studies without empirical data.

Selected studies were critically analyzed to synthesize information on *M. anisopliae* virulence, application methods, field effectiveness, and integration into pest management strategies. This approach ensures a comprehensive, up-

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https://doi.org/10.29244/jtcs.13.01.134-147

to-date overview of current knowledge and identifies gaps for future research.

Scientific Classification of *Metarhizium anisopliae*

Metarhizium anisopliae (Metsch.) Sorokin is an entomopathogenic fungus classified under the kingdom Fungi, phylum Ascomycota, and class Sordariomycetes (Sharma & Sharma, 2021). Within this class, it is placed in the order *Hypocreales* and the family Clavicipitaceae (Zhang et al., 2023). The genus *Metarhizium* comprises several species, with *M. anisopliae* being widely recognized for its efficacy in biological pest control across a broad spectrum of insect hosts (Yapa et al., 2025). Previously known as *Entomophthora anisopliae*, this fungus is naturally soil-borne and found globally (Kobmoo et al., 2024). It parasitizes insects, thereby classifying it as an entomopathogenic fungus, and is known to infect over 200 insect species, including termites (Syazwan et al., 2021).

The species name of *M. anisopliae* originates from its first isolation from the beetle *Anisoplia austriaca* (Bischoff et al., 2009). It is a mitosporic fungus that reproduces asexually, and to date, no teleomorph (sexual stage) has been identified. While some evidence suggests a possible relationship to the genus Cordyceps, as observed in *Cordyceps taii*, the teleomorph of *Metarhizium taii*, it is also likely that many strains of *M. anisopliae* have lost the capacity for sexual reproduction (Baral, 2017).

Metarhizium anisopliae Pathogenesis

The infection process of entomopathogenic fungus *M. anisopliae* is complex and essential to its function as a biopesticide. The pathogenic cycle begins when conidia (asexual spores) land on the insect cuticle. Hydrophobic proteins on the conidial surface mediate initial adhesion, while exogenous lectins facilitate host-specific recognition by binding to insect epidermal glycoproteins (Peng et al., 2022). The adhesin protein Mad1 also plays a crucial role in anchoring germinating conidia to the insect surface, potentially compensating for the degradation of hydrophobins (Zhou et al., 2021). Hydrophobins are small, cysteine-rich proteins produced by filamentous fungi that self-assemble into an amphipathic layer at interfaces to alter surface properties, making hydrophobic surfaces wettable.

Following adhesion, the fungus secretes lipases to degrade the lipid-rich outer layer of the cuticle, enabling penetration (Karthi et al., 2024). This enzymatic activity is central to overcoming the insect's external defense mechanisms (Devi, 2021). Once inside, fungal hyphae proliferate in the hemocoel, where they compete for nutrients and secrete chitinases and proteases to break down host tissues (Ma et al., 2024). Ultimately, the fungus kills the host by nutrient depletion and tissue destruction (Fei & Liu, 2023). Sporulation then occurs on the insect cadaver, producing new conidia that can disperse and initiate subsequent infections (Qiu et al., 2021). This coordinated sequence —from adhesion and penetration to colonization, host death, and sporulation — underscores the fungus's effectiveness as a biological control agent.

Symptoms and Visual Manifestations of Infection

The disease caused by Metarhizium anisopliae is commonly referred to as green muscardine disease, named after the olive-green coloration of mature conidia (Nwaokolo et al., 2023). Upon contact with the host, conidia germinate, and hyphae penetrate the cuticle (Arya et al., 2021). Early signs of infection include the appearance of white fungal hyphae on the cadaver, which later turn green as sporulation progresses (Byrne & Rankin, 2021). Fungal colonization fills the insect body with mycelia, and once internal contents are depleted, the fungus breaches the cuticle, resulting in a characteristic fuzzy appearance (Ma et al., 2024). Depending on the strain and environmental conditions, the color of conidia can vary from white and yellow to brown and green (Nwaokolo et al., 2023). Initial internal infection is not externally visible.

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However, as colonization advances, affected insects may display lethargy, color changes, and altered behavior, precursors to mortality (Ma et al., 2024). The culmination of infection was marked by external sporulation, where conidiophores produce powdery conidia masses, signaling the end of the fungal life cycle and the potential for environmental dissemination (Amaresan & Kumar, 2025).

Favorable Environmental Conditions for *M. anisopliae*

The efficacy of *M. anisopliae* as an entomopathogenic fungus is highly dependent on environmental conditions (Quesada-Moraga et al., 2024). Optimal growth and sporulation occur at temperatures between 25 °C and 30 °C (Sani et al., 2023). High relative humidity, typically above 70%, is crucial for conidial germination and host infection (Agbessenou et al., 2021). Soil conditions also influence fungal performance; slightly acidic to neutral pH (6.0–7.0) and well-drained, organic-rich soils are most favorable (Khan & Gang Wang, 2023). Environmental stressors, such as UV radiation, can significantly reduce conidial viability by inducing DNA damage (Tong & Feng, 2022). Temperature extremes also affect fungal metabolism; heat can lead to desiccation, while cold limits growth (Zimmermann, 2007). Sufficient moisture is essential, as dry conditions hinder conidial germination and infection (Yousef-Yousef et al., 2022).

Interestingly, *M. anisopliae* can form symbiotic associations with plant roots, enhancing its survival in the rhizosphere and facilitating nutrient exchange (Murindangabo et al., 2024). Behie et al. (2015) demonstrated nitrogen transfer from insect prey to host plants, positioning *M. anisopliae* as both a biocontrol agent and a plant symbiont. However, competition with native microbial communities presents a challenge. Soil and phyllosphere microbes can inhibit fungal establishment through resource competition or the production of antimicrobial compounds (Xu et al., 2022). Additionally, some researchers argue that *M. anisopliae*'s role as an endophyte may be incidental rather than an inherent trait, with soil contact being its primary ecological niche (Bamisile et al., 2021; Zimmermann, 2007).

Cacao, a highly valued tropical crop, may not provide ideal conditions for endophytic colonization by *M. anisopliae* (Thube et al., 2022). The cacao microbiome and fluctuating tropical climate introduce biotic and abiotic stressors that hinder fungal establishment (Jaimes-Suárez et al., 2022). Moreover, cacao plants produce antimicrobial compounds that act as barriers to colonization (Ben Lagha et al., 2021). Studies by Faria and Wraight (2007) and Lopez and Sword (2015) underscore the importance of optimizing field conditions to enhance the persistence and efficacy of *M. anisopliae* as a biocontrol agent and potential endophyte.

Metarhizium anisopliae Host Specificity

In general, *M. anisopliae* exhibits a broad host range, infecting over 200 insect species across several orders, including Coleoptera (beetles), Lepidoptera (moths and butterflies), Hemiptera (true bugs), and Diptera (flies) (Karthi et al., 2024; Yapa et al., 2025; Zimmermann, 2007). This broad spectrum of activity enhances its appeal as a biological control agent in integrated pest management (IPM) programs (Rajput et al., 2024).

Despite its generalist nature, strain-specific differences in host preference and virulence are well-documented. Certain isolates demonstrate enhanced pathogenicity toward specific pests, suggesting intraspecific variation driven by coevolutionary pressures or ecological adaptations (Zhang et al., 2024). For example, strains targeting the cacao pod borer (*C. cramerella* Snellen) may exhibit different infection efficiencies compared to those isolated from other hosts (Arias et al., 2025).

This variability necessitates thorough screening and characterization of isolates prior to field deployment to ensure host specificity, efficacy, and environmental safety (Vashisht et al., 2023). In agricultural systems, such as cacao plantations, selecting *M. anisopliae* strains with

Received 10/05/2025; Revised 06/10/2025; Accepted 17/10/2025
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high virulence against the cacao pod borer while minimizing non-target effects is crucial to prevent unintended ecological consequences (de Sousa et al., 2025).

Metarhizium anisopliae Endophytic Activity

Beyond its entomopathogenic role, *M. anisopliae* can live as an endophyte within plant tissues, where it may confer additional benefits to the host (Bamisile et al., 2021). Endophytic colonization refers to the asymptomatic presence of the fungus within a plant's internal tissues, including roots, stems, and leaves (Dos Reis et al., 2022). This dual functionality, as both an insect pathogen and a plant symbiont, offers promising avenues for sustainable crop protection (Lv et al., 2024).

Studies have shown that *M. anisopliae* can colonize a range of crops endophytically, including maize, tomato, and cacao (Ahsan et al., 2024; Aravinthraju et al., 2024; Mwamburi, 2021). Such colonization can lead to systemic resistance against insect pests and some phytopathogens, possibly mediated through induced systemic resistance (ISR) or secondary metabolite production (Hu & Bidochka, 2021). Moreover, the endophytic character of *M. anisopliae* has been linked to improved nutrient uptake and plant growth promotion (Behie et al., 2015).

However, successful colonization is influenced by several factors, including plant genotype, fungal strain, inoculation method, and environmental conditions (Lopes et al., 2021). While root and stem colonization are relatively common, persistence in foliar tissues is often lower and more transient (Hu & Bidochka, 2021). The potential for *M. anisopliae* to colonize cacao plants endophytically remains underexplored. Environmental challenges in tropical ecosystems, such as high microbial competition and the presence of antimicrobial plant compounds, may hinder sustained colonization (Mathur & Ulanova, 2023). Thus, while endophytes offers added value, its consistency and contribution to pest suppression in cacao systems require further empirical validation (Alvarez-Romero et al., 2025).

Efficacy Against Cacao Pod Borer (CPB)

The cacao pod borer, known as *C. cramerella*, is the major insect pest in Southeast Asia, particularly in cacao-growing regions such as the Philippines, Indonesia, and Malaysia (Amalin et al., 2023). Infestation by CPB leads to significant yield losses, often exceeding 50%, and compromises pod quality and marketability (Adeniyi & Asogwa, 2023). Traditional management relies heavily on chemical insecticides, which pose risks to human health, biodiversity, and environmental sustainability (Pathak et al., 2022).

Biological control using *M. anisopliae* offers a promising alternative. Laboratory and semi-field studies have demonstrated the fungus's pathogenicity against CPB, leading to reduced larval survival and adult emergence (Aryal et al., 2025). Conidia applied directly to cacao pods or incorporated into soil can infect CPB during different life stages, particularly the larval and pupal stages, which are vulnerable due to cuticle exposure (Montecalvo and Navasero, 2021).

Metarhizium anisopliae has been identified as a promising entomopathogenic fungus for the biological control of the cacao pod borer, a significant pest in cacao production. Ernawati (2013) conducted laboratory studies demonstrating that *M. anisopliae* could infect CPB larvae, resulting in significant mortality. However, field trials are essential to assess the practical efficacy and environmental impact of Ma-based biocontrol agents.

Field studies have shown variable results. For instance, Susila (2011) reported that both *B. bassiana* and *M. anisopliae* were effective in controlling CPB larvae, with *B. bassiana* outperforming *M. anisopliae* at specific spore concentrations. This suggests that while Ma has potential, its effectiveness may vary depending on environmental conditions and application methods. Field trials conducted in Brazil and other tropical regions have reported that *M. anisopliae* typically achieves infection rates of ≤50% against target pests under natural field conditions. This relatively modest efficacy contrasts with higher infection levels

Received 10/05/2025; Revised 06/10/2025; Accepted 17/10/2025
https://doi.org/10.29244/jtcs.13.01.134-147

observed in laboratory settings or against other pests such as locusts and termites. Several factors may account for this difference: (1) environmental conditions such as high UV exposure, rainfall, and fluctuating humidity that reduce spore viability; (2) behavioral traits of pests like the cacao pod borer (*C. cramerella*), which spends much of its life cycle protected within cacao pods, limiting fungal contact; and (3) variability among fungal strains in virulence and adaptability to local microclimates. These limitations highlight the importance of selecting locally adapted *M. anisopliae* strains, improving formulation technology, and integrating the fungus with complementary control methods to enhance field performance.

Further research is needed to optimize the use of *M. anisopliae* against CPB. Studies should focus on isolating local Ma strains with high virulence, determining optimal application methods, and evaluating the impact on non-target organisms. Additionally, integrating *M. anisopliae* with other pest management strategies could enhance its effectiveness and sustainability.

Application methods, such as spraying conidial suspensions or using granular formulations, significantly influence efficacy (Behie & Birthisel, 2023). Environmental factors, such as humidity, temperature, and UV exposure, also affect conidial viability and infection success (Shah & Pell, 2003). To enhance field performance, formulations with UV protectants or oil carriers have been developed to improve adhesion and persistence on plant surfaces (Saminathan et al., 2025).

Despite promising results, field-level effectiveness remains variable. This inconsistency highlights the importance of integrating *M. anisopliae* with cultural practices such as sanitation, pod sleeving, and timely harvest (Bashyala et al., 2022). Combining biocontrol with these IPM components can reduce CPB populations and improve long-term pest suppression (Zhou et al., 2024).

Recent studies have provided updated insights into the biology of CPB. Magfirah et al. (2025) reported comprehensive biological parameters of CPB under laboratory and field conditions, which can inform optimal timing for *M. anisopliae* applications. Purificacion et al. (2024) developed microsatellite markers for CPB, facilitating population monitoring and resistance management. To provide a clear overview of existing research, Table 1 summarizes key studies evaluating the effectiveness of *M. anisopliae* against the cacao pod borer (*C. cramerella*). The table highlights details such as study type, fungal strain, application method, target pest stage, observed mortality or effectiveness, and key findings, facilitating comparison across different experimental conditions and geographic locations.

Damage Caused by Cacao Pod Borer (CPB)

Conopomorpha cramerella, commonly known as the cacao pod borer, is an internal fruit borer that infests cacao pods, causing substantial economic losses (Arias et al., 2025). Adults lay eggs on the pod surface, and upon hatching, the larvae bore through the pod husk and feed on the mucilage and developing beans (Prasad, 2022). This feeding behavior disrupts bean development, reduces bean quality, and promotes fungal infections (Meilin et al., 2023).

Externally, infestation is indicated by premature ripening, brownish lesions, and the presence of frass and exit holes on the pod surface (Cocuzza et al., 2021). Internally, beans are often shriveled, discolored, and coated with web-like silk secretions produced by larvae. In severe infestations, entire pods become unmarketable (Adeniyi & Asogwa, 2023). The economic impact of CPB is profound. Losses include direct yield reduction, increased labor for pest management, and diminished bean quality that affects export standards. In regions such as the Philippines, the pest has contributed to the decline of cacao production and has been a barrier to revitalizing the local cacao industry (Patalinghug, 2022).

Effective management of CPB requires an integrated approach (Rizal et al., 2024). Biological control agents, such as *M. anisopliae*,

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offer a sustainable solution, particularly when combined with cultural practices and regulatory support. Understanding the pest's biology, infestation patterns, and ecological interactions is essential for designing effective IPM strategies that protect yield and improve cacao production systems.

Economic Considerations of *Metarhizium anisopliae* Application

The use of *M. anisopliae* as a biocontrol agent offers several economic advantages compared to conventional chemical insecticides. Although the initial costs of producing and

Table 1

Summary of Key Studies on the Effectiveness of Metarhizium anisopliae (Ma) Against Cacao Pod Borer (Conopomorpha cramerella)

Study	Location	Study type	Ma strain / Focus	Application method / Focus	CPB stage targeted / Focus	Observed mortality / Effectiveness	Key findings
Ernawati (2013)	Indonesia	Laboratory	Local *Ma* isolate	Conidial suspension on larvae	Larvae	5%–90%	High larval mortality; efficacy depends on conidial concentration.
Susila (2011)	Indonesia	Field	*Ma* vs *Beauveria bassiana*	Pod surface application	Larvae	60%–75%	Both fungi effective; B. bassiana slightly more effective at certain concentrations.
Montecalvo & Navasero (2021)	Philippines	Semi-field	Commercial *Ma* formulation	Soil and pod application	Larvae & pupae	70%–80%	Conidia reduced larval survival; environmental conditions influenced results.
Aryal et al. (2025)	Nepal	Laboratory and greenhouse	*Ma* isolate	Spraying conidial suspension	Larvae	80%	Rapid infection under controlled conditions; highlights IPM potential.
Behie & Birthisel (2023)	Various	Review / Field studies	Multiple *Ma* strains	Granular and liquid formulations	Larvae and adults	Variable (50–90%)	Effectiveness depends on strain, formulation, and environmental factors.
Purificacion et al. (2024)	Philippines	Laboratory	CPB genetics	N/A	N/A	N/A	Developed microsatellite markers for CPB, useful for population studies and resistance monitoring.
Magfirah et al. (2025)	Malaysia	Laboratory and Field	CPB biology	N/A	All stages	N/A	Detailed biological parameters of CPB, informing timing and strategies for biocontrol application.

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applying *M. anisopliae* formulations, such as conidial suspensions or granular carriers, may be higher than purchasing standard pesticides, long-term benefits include reduced pesticide use, lower labor costs for repeated applications, and decreased environmental and health risks**.** Field studies suggest that integrating *M. anisopliae* into Integrated Pest Management (IPM) programs can maintain cacao yields while reducing reliance on chemicals, thereby improving cost-effectiveness across multiple cropping seasons.

Additionally, the potential for *M. anisopliae* to persist in the field and act as both a biocontrol agent and endophyte enhances its value, as a single application may confer extended protection against the cacao pod borer (CPB). Sensitivity to environmental conditions and strain selection can influence cost-benefit outcomes, emphasizing the need for locally adapted, high-virulence strains and optimized application strategies. Overall, biological control with *M. anisopliae* represents a sustainable, economically viable alternative to chemical control, particularly for smallholder cacao farmers aiming to reduce input costs and promote environmentally friendly practices.

Summary and Outlook

Metarhizium anisopliae is a well-characterized entomopathogenic fungus with a broad host range, capable of infecting over 200 insect species, including the cacao pod borer (*C. cramerella*). Its pathogenicity involves a coordinated sequence of adhesion, cuticle penetration, internal proliferation, and sporulation, making it an effective biological control agent. Environmental conditions, including temperature, humidity, soil pH, and UV exposure, significantly influence its efficacy. Formulation methods and integration with cultural practices can also enhance field performance. In addition to its entomopathogenic role, *M. anisopliae* can act as an endophyte, potentially improving plant resistance and nutrient uptake, although its persistence in cacao remains underexplored. Laboratory and semi-field studies have demonstrated the potential of *M. anisopliae* against CPB. Still, field trial results remain variable, highlighting the need for context-specific evaluation. The review highlights that strain selection, virulence characterization, application methods, and environmental adaptation are crucial for optimizing biocontrol outcomes. While *M. anisopliae* demonstrates strong biocontrol potential against the cacao pod borer (CPB), several limitations and challenges affect its practical application. Virulence and host specificity vary among *M. anisopliae* strains, meaning that isolates effective in one region or against one host may not perform similarly elsewhere, highlighting the importance of selecting locally adapted, highly virulent strains. Field performance is susceptible to environmental conditions, such as temperature, relative humidity, UV radiation, and soil characteristics. Optimal efficacy generally requires temperatures of 25–30 °C and relative humidity above 70%, while extreme conditions can reduce conidial viability and infection rates. Laboratory and semi-field trials often report CPB mortality rates of 80%–90%, yet field-level effectiveness is variable due to fluctuating environmental factors, pest behavior, and interactions with native microbial communities. Application methods and formulation also influence success, with oil-based or UV-protectant carriers improving conidial adhesion, persistence, and infection, whereas poorly formulated products can limit field efficacy. Although *M. anisopliae* can function as an endophyte, its colonization in cacao plants is inconsistent due to variations in plant genotype, the presence of antimicrobial compounds, and microbial competition. Finally, *M. anisopliae* is most effective when integrated with cultural practices such as sanitation, pod sleeving, and timely harvesting, as standalone applications may not achieve sustainable pest suppression. Addressing these constraints through careful strain selection, optimized formulations, and integration with complementary IPM strategies is essential to maximize the effectiveness and sustainability of *M. anisopliae*-based biocontrol in cacao agroecosystems. Future studies should focus on isolating locally adapted, highly virulent

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M. anisopliae strains and conducting rigorous field trials to assess efficacy under diverse environmental conditions. Research should also explore integrating *M. anisopliae* with other biological and cultural management strategies for sustainable CPB control. Furthermore, the potential of *M. anisopliae* as an endophyte in cacao plants requires empirical validation, including its effects on pest suppression, plant growth, and interaction with the native microbiome. By addressing these knowledge gaps, researchers can strengthen integrated pest management programs and enhance the sustainability of cacao production in regions affected by CPB. Based on a synthesis of the current literature, future research should focus on conducting additional field trials to evaluate the efficacy of *M. anisopliae* against cacao pod borer (CPB) under diverse environmental conditions. Studies should aim to identify locally adapted, highly virulent strains, optimize application methods, and assess potential impacts on non-target organisms. Additionally, comparative research integrating *M. anisopliae* with other biocontrol agents and conventional pest management strategies is encouraged to develop effective, sustainable, and scalable control programs for CPB.

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